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THE FORMATION OF LEUCITE IN IGNEOUS ROCKS

Continued

HENRY S. WASHINGTON

COMPARISON

In the preceding discussion we have dealt only with norms or ideal rocks, of simple chemical compositions, and with perfectly normative modes composed of a few standard minerals alone. In these the relations are purely chemical, and the order of affinity for silica has been assumed to be invariable. But we have now to consider igneous rocks as they actually exist in nature. In dealing with them the problem becomes much more complex, not only through the introduction of a greater number of chemical and mineral constituents, but on account of the presence of several factors, both intrinsic and extrinsic to the magma or the rock, which may greatly modify our assumedly invariable orders of affinity.

We must remember that few of the standard minerals present in rocks are ever as simple in composition as they are assumed to be in calculating the norm. Thus a purely potassic orthoclase seldom occurs, this mineral almost invariably containing varying, though often small, amounts of soda and lime. Similarly with albite and anorthite, which tend to crystallize together, as well as to contain frequently small quantities of the orthoclase molecule. Leucite usually carries small amounts of soda and lime, while modal nephelite is never a simple, purely sodic, orthosilicate, but invariably contains small percentages of potash, giving rise to a more complex formula. The development in very many rocks of the alferic augites, hornblendes, micas, and other minerals, with numerous chemical constituents and highly complex molecules, is also an important fact to be taken into consideration.

Again, the fact that the crystallization of minerals changes the composition of the remaining fluid portions of the magma must not be lost sight of, and finally the influence of such factors as the mass action of complex mineral molecules, the physical conditions of

cooling, the presence of mineralizers, and so forth, upon the order of affinity are all important elements in the problem. The list of these possibly disturbing factors is a long one, and the established facts of chemistry show that affinities which hold good, or reactions which take place, under certain conditions may be much modified or entirely altered under others.

Bearing these possibilities in mind, we may proceed to the comparison between the actual rocks and our assumed norms. This may be done by plotting the rocks on the same diagram as our theoretical areas, and observing the correspondences and divergences, for which we may again turn to Plate II (p. 270).

The rocks chosen for comparison embrace practically all those known to me which carry modal leucite, whether or not it is present in the norm, and those which show normative but not modal leucite. Some seriously altered rocks are omitted, and only rocks of which superior, trustworthy analyses exist, and of which the norms can be properly calculated, have been selected. With these are also plotted certain rocks which do not carry leucite either in the norm or in the mode, but which are high in potash, as well as a few which are not specially high in potash, but which belong to the same comagmatic regions as leucitic rocks, and are genetically connected with them. The list of the non-leucitic rocks could be increased very greatly, as they form the vast majority of all known rocks; but the plotting of an indefinitely large number would not aid the present discussion, so that only those few are chosen which fall near the leucitic areas or which seem to bear on the problem.

The analyses are taken from Roth's *Tabellen*, from my collection of rock analyses published between 1884 and 1900, from the recent paper on the rocks of the Roman Comagmatic Region, and from numerous analyses published since 1900, of which a collection is being made preparatory to the publication of a supplement to the first. A list of those plotted will be found in the Appendix.

Nearly all of these analyses are plotted on Plate II, the abscissa being the percentage of silica and the ordinate that of potash, both expressed molecularly. The following conventional signs are adopted: Black indicates a persalane rock, green a dosalane, and red a salfe-mané or dofemané rock. A circle denotes that leucite is present in

the norm, and a square that leucite is not present in the norm. A solid color denotes that leucite is present in the mode, and a simple outline with uncolored interior that leucite is not present in the mode. Thus a solidly colored circle shows that the rock contains leucite both in the norm and in the mode; a solidly colored square, that it contains no normative leucite, but that this mineral occurs modally; an uncolored circle, that, while the norm of the rock shows leucite, none of this has actually developed; and finally, an uncolored square, that the rock is not leucitic, either normatively or modally.

The first general survey of Plate II shows that the general position and drift of the leucite rocks correspond well with the plotted areas of leucitic norms, $L^1O^1N^1$ to $L^9O^9N^9$. A very few fall outside and to the left of these limits, these rocks being without normative leucite, and some to the right of the area $L^9O^9N^9$, these being all normatively leucitic, but modally either leucitic or non-leucitic. The general direction of the axis of this area of the loci of leucitic rocks, or its drift, as it may be termed, is distinctly parallel to that of the inclination of the leucitic areas, especially to that of the lines ON .

Again, it will be observed that the abnormatively modal rocks (as regards leucite) lie for the most part toward the extreme right and left, while those which are normatively modal as regards the presence of leucite (represented by colored circles) occupy in general an intermediate position. Thus the rocks with leucite in the norm but not in the mode, and therefore abnormative in this respect, (represented by uncolored circles), are found, with few exceptions, well to the right or toward the low silica side of the diagram. On the other hand, the rocks with leucite in the mode but not in the norm (represented by colored squares) are almost all well toward the left or toward the side of high silica, and those free from either normative or modal leucite still more to the left.

A further fact which is to be noted is that none of the rocks with abnormatively modal leucite fall inside the quartz-orthoclase-albite area OAQ , in this conforming to the conclusion reached above, that leucite is not formed from magmas with an excess of silica or normative quartz.

Advancing more into details in our comparison, we must determine whether the rocks with leucite in the norm, or in the mode, or in both,

fall within the leucitic areas corresponding to their content in molecules of anorthite and femic minerals. This is the crucial test of the validity of our assumed order of affinity for silica; for it follows from the preceding discussion that for any given set of magmas containing a definite amount of anorthite and femic molecules in the norm (however these may be crystallized in the mode), but with varying amounts of silica and potash the loci of normatively leucitic rocks (which should also be modally leucitic) derived from them should fall within the corresponding leucitic area; and those free from normative leucite (which should also be free from this in the mode) should fall outside of this, either to the right or to the left.

We have seen that the introduction of salic lime into the magma causes only a slight change in the positions of the leucite-nephelite and orthoclase-nephelite boundaries of the leucitic area, though it has a much greater effect on the leucite-orthoclase boundary above, lowering this very decidedly. The effect of the introduction of the constituents of the femic minerals, on the other hand, is much more marked and varied in its character. The leucitic area shifts somewhat to the left if pyroxene enters into the norm,¹ while with olivine, and with magnetite and other minerals free from silica, the shift is still greater and toward the right or less siliceous end. At the same time, the upper boundary is lowered to an extent even greater than is caused by salic lime. It is to be remembered, however, that, whatever the constituents thus introduced or assumed to be present, the angle LNO and the inclination of the leucitic area to the horizontal line $QAMN$ do not vary, the lines LN and ON always being parallel. A few simple cases have been plotted on Plate II, but it is obvious that, for purposes of adequate comparison of actual rocks with their theoretical leucitic areas, some means must be had of determining the true position of the leucitic area corresponding to any given rock, whatever be its composition and however complex it may be as regards its mode or norm. Fortunately this determination is not difficult, nor does it involve an inordinate amount of calculation.

The method consists, in brief, of the calculation of the locus (expressed in terms of the percentages of silica and of potash) of one

¹ This shift toward higher silica would be still greater if aegirite enters into the problem, as it not infrequently does.

or more definite points of the leucitic area desired, when its size and position on the diagram can be readily laid down, the parallelism of the various lines here coming into use, and its relations to the locus of the rock can be studied. For this purpose any two of the points *L*, *O*, or *N*, may be used, but for practical purposes the simplest determination is that of the point *N*, the locus of a mixture of nephelite with the amounts of normative anorthite and femic minerals corresponding to the rock. From this the directions of the points *L* and *O* may be readily determined.

The actual process is as follows: The norm of the rock having been calculated in the usual way, the total percentage of the normative anorthite and combined femic molecules, and the total amount of silica belonging to them, are estimated. The difference between their combined percentage 100 per cent. is then assumed to be nephelite, and the amount of silica belonging to this is calculated. The sum of these percentages of silica (those of normative anorthite, femic minerals, and of nephelite) is then reduced to molecular ratio by dividing by 60, and the result is the locus *N* of the leucitic area corresponding to the rocks on the abscissal line QANM. The leucite-nephelite and orthoclase-nephelite boundaries of this area are determined by drawing lines from *N* parallel to the other *LN* and *ON* lines of the diagram, the points *L* and *O* being readily determined by calculating the amount of potash or silica corresponding to a mixture of anorthite + femic molecules and either leucite or orthoclase, respectively, in the same proportions that were used in the case of nephelite.¹

In actual practice, however, it was found that the determination of the points *L* and *O* was seldom necessary, and the comparison between the leucitic area and the locus of the rock was accomplished without defacing the plotted diagram and very quickly, after the point *N* had been determined, by means of a square sheet of stiff paper from which a triangle had been cut, whose lower angle *LNO* and inclination as regards the lower edge of the paper corresponded to those of the plotted leucitic areas in the diagram. By placing the sharp lower apex of this triangular opening at the determined point *N*,

¹ The locus of *N* for every rock, as thus calculated, is given in the list of analyses in the Appendix.

keeping the lower edges of the sheet and of the diagram parallel, it could easily be seen if the locus of the rock fell within or without its corresponding leucitic area.¹

It should be said that, in any such study of the relations of rocks to their theoretical areas, the data will be, of course, strictly comparable only if the analytical figures are reduced to the same condition, by eliminating water and other nonessential ingredients and by recalculating the remainder to 100 per cent. To render our comparisons strictly accurate, this should have been done for all the analyses whose loci are shown on Plate II. But this would have involved a very considerable amount of work and the expenditure of much time, which the study did not seem to warrant, especially as it was found that the changes in position thus brought about were for the most part so small as to be negligible in the scale of the diagram here given, except in the case of some manifestly altered rocks, the greater number of which have been omitted.

On examination of the diagram in this way it was found that, making due allowance when necessary for rather large amounts of water, carbon dioxide, etc., the loci of all the rocks with normative leucite fell inside their respective leucitic areas, with two exceptions, Nos. 92 and 177, which fall to the right of the area. But the norms of these show the presence of kaliophilite, there being therefore an excess of potash, so that their position is quite in accordance with our assumptions. Of the rocks without normative leucite the loci fall outside of the leucitic areas, with the exception of Nos. 104, 105, and 106, orendites and a wyomingite of the Leucite Hills. But these also have an excess of alkalies, as shown by the presence of potassium metasilicate in the norm, so that, while they should fall to the left of the line *ON*, being free from normative leucite, the large amount of potash raises their loci so as to make them fall inside the leucitic area. It must also be borne in mind that the rocks free from normative leucite include the vast majority of all known rocks, only a few of which are plotted in the diagram, and concerning whose locus outside the leucitic area there can be no question. We may therefore consider the proposition as established, namely, that the

¹ A square sheet of thin, transparent celluloid, properly marked, would be better than the paper.

locus of a rock will fall inside or outside its corresponding leucitic area according as it does or does not show leucite in the norm.

It will be observed that the great majority of these rocks which show both normative and modal leucite are distinctly high in potash, for the most part containing over .050 mol. prop. of K_2O , and that silica and potash both tend to increase with decrease in the amount of femic molecules, the black and the green circles lying above and to the left, and the red ones to the right and below; also the range in silica is greater with increasing potash. A study of the list of analyses will show that, with the exception of a leucite-syenite of Magnet Cove and the missourite of the Highwood Mountains, all these rocks are effusive flows.

But there are a considerable number of cases which do not conform to our assumed order and which are to be regarded as constituting exceptions to the rule, and which therefore demand an explanation. These exceptions are of two kinds—namely, rocks with normative leucite, but free from it in the mode, though falling inside their leucitic areas; and rocks with leucite developed modally, though free from it normatively, and falling outside their leucitic areas. The loci of the first kind of these exceptions, indicated by uncolored circles, fall for the most part well toward the less siliceous end of the diagram, and most of these rocks are low in potash and belong to the *salfemane* class. The loci of the other kind of exceptions, indicated by colored squares, fall mostly well toward the more siliceous end, the rocks are often quite high in potash, and they are pretty well distributed among the *persalane*, *dosalane*, and *salfemane* classes.

The cases of the first kind are exceptional, and do not conform to the assumed order of affinity, because no leucite has crystallized, though it should be present according to our theory; while the cases of the second kind are exceptional in that albite has been formed rather than nephelite, and leucite rather than orthoclase, at least in part, in these soda having an apparently greater affinity for silica than has potash.

But before considering these exceptions it will be pertinent to the discussion to assume another order of affinity, and to calculate the norms and their loci on the basis that soda has a greater affinity for silica than potash has, or, expressed mineralogically, that albite

will form rather than nephelite, and leucite rather than orthoclase, in which respect the cases of the second kind are peculiar. For this purpose we need only consider the simplest case, that of a persalic and peralkalic magma, without excess of silica and with alumina equal to the total alkalis, as formerly.

It is clear that on this assumption the line representing purely feldspathic norms, composed only of orthoclase and albite, will be identical with that calculated on the previous assumption. It will be the line O^1A^1 on Plate II (p. 270). Also the line representing purely lenic norms, composed only of leucite and nephelite, will coincide with L^1N^1 . Similarly, if the magmas are perpotassic (that is, quite free from soda), the upper limiting line will coincide with the previous one $L^1O^1Q^1$.

The divergence from the previous assumption will be expressed by the line representing norms composed only of albite and leucite, along which these are in equilibrium, so that magmas with less silica for any given percentage of potash will yield norms composed of albite, nephelite, and leucite, while those with more silica will yield norms composed of orthoclase, albite, and leucite. This is the dotted black line L^1A^1 of Plate II. The orthoclase-albite-leucite area $L^1O^1A^1$ is comparatively small, and with a range in silica only from that of albite to that of leucite, while the albite-leucite-nephelite area $L^1A^1N^1$ is much larger and with a range in silica from that of albite to that of nephelite.

On this assumption, therefore, we should expect to find very many more rocks with leucite than rocks with orthoclase, and orthoclase rocks should be relatively less abundant on this assumption than should leucite rocks be on the other. Also we could expect to find leucite rocks with silica percentages up to 68.70, and the range in silica of leucitic rocks should increase with decreasing potash. It need scarcely be pointed out that the facts of petrography are directly contrary to these deductions. Furthermore, not a single leucite rock falls within the area $L^1O^1A^1$,¹ and the position of the line L^1N^1 , and the shape and position of the areas $L^1O^1A^1$ and $L^1A^1N^1$, are wholly discordant with the positions of the leucitic rocks as actually observed and plotted. Similar discordances would be observed were

¹ The apparent exception seen in the diagram will be discussed later.

the affinity of other oxides for silica, as lime, magnesia, or ferrous oxide, assumed to be greater than that of potash; but these need not be discussed here.

The general coincidence between fact and theory on the first assumption, and the grave discordance observed on the second, are clear proof that the former is in general the correct one, and that, while some exceptions do exist, in the vast majority of cases potash has a greater affinity for silica than soda has. Dismissing, therefore, any other assumption as to affinity for silica than the one with which we started, we may proceed to examine the exceptional cases mentioned above. These show clearly that our assumed order of affinity, while valid in most cases, is not a constant one, but that it can be superseded by other factors, into the character of which we have now to inquire.

Considering first the rocks with normative but not modal leucite, it is found that a large proportion of them are effusive rocks containing glass, their incomplete crystallization rendering their evidence inconclusive. It will be observed, however, that the great majority of these glassy rocks, while low in silica, are relatively high in alkalis, especially soda. The list of analyses shows that they are mostly nephelinites and nephelite-basalts in common parlance, all belonging to the lenic orders, and that most of them are dosodic. Their incomplete crystallization is in accord with this relatively alkalic character, as the researches of Lagorio and others show that such alkalic magmas are prone to undercooling and the formation of glass. From what we know of the order of crystallization which generally obtains in effusive rocks, and the usually late appearance of leucite, it is highly probable that leucite would have formed, in many cases at least, had the conditions permitted complete crystallization. We may therefore reasonably eliminate these from the list of exceptions on the presumption that, had they been holocrystalline, they would have been modally leucitic and hence not exceptional.

But again we find a very considerable number of perfectly holocrystalline rocks with normative but not modal leucite, represented by uncolored circles. These, it will be observed, are apt to fall toward the lower part of the diagram; that is, they are poor in potash: and they lie for the most part well toward the right; that is, they

are low in silica. Furthermore, the greater part of them contain large amounts of femic minerals, falling in salfemane and dofemane, with a few in dosalane, and none at all in persalane. Again, it will be observed that, with some exceptions, especially of melilite-basalts, they are all intrusive bodies, which have therefore solidified under conditions very different from those of the effusive flows, as are almost all of the rocks with both normative and modal leucite.

Of these exceptional rocks some contain very considerable amounts of biotite, as Nos. 109, 140, 159, 164, and 193. These rocks are all intrusive, and the conditions of solidification were such that the potash, in combination with magnesia and ferrous oxide, and in the presence of mineralizers, formed the complex biotite molecule, instead of leucite and olivine, as would have been the case under other circumstances. It may be noted, however, that in biotite the potash controls as much or more silica than it does in leucite, and thus conforms to the assumed order of affinity. Thus, if the molecule of biotite be written as $(K,H)_2O.(Al,Fe)_2O_3.2SiO_2 + n[2(Mg,Fe)O.SiO_2]$, the ratio of SiO_2 to K_2O in the salic portion is that of leucite if $K : H$ be $1 : 1$, while it is that of orthoclase if it be $1 : 2$, as is usually the case. Consequently, while the physico-chemical conditions have brought about the formation of the very complex mineral biotite instead of the more simple minerals leucite and olivine, the assumed order of affinity may be considered to hold good.

Others of these exceptions, as Nos. 73, 125, 127, and 178, are rocks which consist very largely of hornblende or augite, and the norms of which contain very small amounts of leucite, only from 1 to 3 per cent. In these cases the amount of potash present is relatively so small that a great affinity for silica might be readily masked or overcome by the mass action¹ of the complex molecules of the minerals which make up most of the rock, and which would incorporate the small amount of potash in their molecules.

Some other cases are of ijolites and urtites, rich in nephelite and aegirite or aegirite-augite, as Nos. 100, 101, 102, 103, 158, 170, and 171. The formation of the sodic pyroxene in these is conditioned by the excess of alkalis over alumina and the presence of ferric oxide, and as the soda in this controls twice as much silica as it does in nephe-

¹ Cf. S. L. Penfield, *American Journal of Science*, Vol. XXIII (1907), p. 25.

lite, relatively less is left for the potash. The latter enters into the modal nephelite, which, as we know, always contains considerable potash and apparently has a rather complex molecule. Nephelite is present in very large amounts in these rocks, so that its mass action, as well as that of the abundant and complex pyroxene (which often contains some potash), may reasonably be considered to come into play in capturing the potash and preventing the formation of leucite. It is highly probable, also, that the physical conditions enter in as factors, since the rocks just discussed are all intrusive, while we find some with very similar chemical characters (as Nos. 99, 162, and 163) which have solidified at or near the surface and which contain much modal leucite, in spite of their high content of soda.

There are also some melilite basalts (Nos. 146, 157, 179, 186, 187, 188, 194, and 195), in which glass is present either in very small amount or not at all, so that the absence of leucite from these effusive rocks cannot be ascribed to incomplete crystallization. This is to be attributed rather to the mass action of the abundant, complex melilite, which always contains some potash; to the comparative richness of these rocks in soda, and the consequent forcing of part of the potash into the abundant nephelite; and in some instances to conditions which favored the stability of biotite, as in the alnoal types (alnoites).

Let us now examine the exceptions of the other sort, those with abnormative modal leucite. These are exceptional in that, although the magma contained sufficient silica to permit the entrance of all the potash into orthoclase, as an actual fact this constituent did not take all of its theoretical quota of silica, but was content with less, forming leucite in whole or in part.

Examining the norms of these rocks, it is found that, with a few exceptions to be discussed later, they are all deficient in silica, normative nephelite and olivine being present in every case. Therefore the silica liberated through the formation of leucite instead of orthoclase by the potash could form either albite from the normative nephelite, or pyroxene from the normative olivine, or both. We find, however, that olivine is present modally in nearly all these rocks, and that they contain almost constantly abundant albite, either in soda orthoclase, or in plagioclase, or in both of these. Furthermore,

my comparative study of the norms and modes of the Italian leucitic rocks¹ showed that it was more frequently the normative nephelite rather than the normative olivine which became silicated, though the latter may also take up silica. It follows then in these cases that, not only did the potash show a less affinity for silica than did the soda, at least in part, but that the soda had a greater affinity for silica than had the magnesia and ferrous oxide. This latter fact, it will be observed, is in perfect harmony with the order of affinity for silica assumed as fundamental in the calculation of the norm and mentioned above.

One more fact is to be noted in this connection—namely, that, while the amount of leucite formed varies much, even attaining the maximum possible in some cases, the silica liberated is never more than what may be completely used up in the formation of either albite or pyroxene, so that we never find an excess of it which would be crystallized as quartz. This is in accordance with the conclusion reached from the study of the diagrams, that quartz should not occur with leucite; and this applies as well to nephelite.

These exceptional cases, represented by colored squares, fall toward the left side of the diagram, extended over a rather broad oblique zone, which is approximately the space between the lines O^6N^6 and O^4N^4 , only a few being to the right of this on the less siliceous side, while rather more fall to the left of O^4N^4 . As regards potash they vary widely, from about .025 to .125. In connection with their distribution it must be remembered that, were all known rock analyses plotted, this space would also contain a much greater number of uncolored squares, representing rocks free from both normative and modal leucite, only a few of which are presented here.

This zone, occupied by rocks which are normatively free from leucite, but which may or may not carry it in the mode, is that of the magmas which have been referred to as “critical” ones, as regards the formation of leucite, this implying that they are in a nicely balanced condition chemically, so that a comparatively slight change in the

¹ *The Roman Comagmatic Region* (Carnegie Publication No. 57, 1906), pp. 155, 187. Cf. also A. Lacroix, *Comptes Rendus*, Vol. CXLI (1905), p. 1191, who shows that in some cases much of the olivine may take up silica, and so induce the formation of leucite, when the soda is so low that the entrance of all of it into albite may not do this.

physical conditions during solidification may induce or prevent the formation of leucite.

It has been noted above that the replacement of orthoclase by leucite may take place to varying degrees, and when the positions of these colored squares are compared with their respective leucitic areas, it is found that, as a general thing, the nearer they lie to these, the richer they are apt to be in leucite, and the more completely the potash has entered this mineral; while the farther away they are, the poorer the rock is in leucite. So that it may be said that the tendency to form leucite increases with the nearness of the locus of the rock to its leucitic area, or as silica and soda decrease and as potash increases, other things being the same.

Indeed, an examination of the published descriptions of the rocks which fall well to the left of and far from their leucitic areas reveals the fact that the amount of leucite in most of them is very small, and that this mineral is made prominent in the name chiefly because of its rarity, and of the desire to distinguish varieties containing it, even in small amounts, from similar rocks which are free from it. These cases would include such rocks as the leucite-banakites and shoshonites of the Yellowstone National Park, the leucite-kulaite of Phrygia, leucite-tephrites of Bohemia, and leucite-rhomben-porphyrines of Kilimanjaro, and many others, into the details of which it is unnecessary to enter here.

But, even granted the accessory character of the leucite in these rocks, they still do not conform to our assumed order of affinity. There are also those rocks in which the abnormative leucite forms an essential and abundant component; and, furthermore, we have to take into consideration the fact that in the rocks with both normative and modal leucite the amount of the latter almost always exceeds that of the former, so that actually a greater amount of leucite has been formed than is demanded by theory.

In this connection it will be of interest to give a few illustrations of such relations of norm and mode, so as to show the extreme variations which are possible, and the actual divergencies in some cases. In the adjoining table are given the norms of some Italian leucitic rocks, in which the amount of modal leucite has been estimated. The columns headed "a" are calculated on the regular assump-

tion that potash, and those headed "b" on the assumption that soda, has the greater affinity for silica. The amount of leucite actually present in the rock is given in the legend below.

	I		II		III		IV	
	a	b	a	b	a	b	a	b
Or.....	52.26	27.52	50.04	26.69	61.72	10.56	11.20	none
Ab.....	17.29	28.82	15.20	26.20	0.52	24.63	none	11.00
An.....	8.62	8.62	12.23	12.23	9.45	9.45	13.07	13.07
Lc.....	none	19.40	none	18.31	none	40.11	26.60	35.32
Ne.....	6.25	none	5.94	none	13.06	none	12.78	6.84
Di.....	6.05	6.05	7.17	7.17	7.98	7.98	23.55	23.55
Ol.....	1.05	1.05	1.87	1.87	1.97	1.97	6.05	6.05
Mt.....	4.41	4.41	3.94	3.94	2.32	2.32	3.48	3.48
Il.....	1.06	1.06	1.37	1.37	1.52	1.52	0.76	0.76
Hm.....	0.80	0.80
Ap.....	0.94	0.94	0.53	0.53	0.34	0.34	1.77	1.77

I. Bagnoreale ciminose (leucite-trachyte). Bagnorea, Vulturnian District (*Rom. Com. Reg.*, p. 68). Modal leucite = 8.8 per cent.

II. Bagnoreale ciminose (leucite-trachyte). Monte Venere, Ciminian District (*Rom. Com. Reg.*, p. 69). Modal leucite = 16.9 per cent.

III. Foglianale vicose (leucite-tephrite). Monte Fogliano, Ciminian District (*Rom. Com. Reg.*, p. 93). Modal leucite = 40.6 per cent.

IV. Scalale braccianose (leucite-tephrite). La Scala, Mount Vesuvius (*Rom. Com. Reg.*, p. 120). Modal leucite = 35.6 per cent.

On comparison of the norms and modes it will be seen that in I only about half the maximum possible amount of leucite has developed, in II the maximum is nearly reached, and in III and IV the whole amount of the potash possible has gone into leucite, no orthoclase being present in the mode of the last rock.*

It is evident that the problem is fundamentally different from that presented by the former sort of exceptions, where the absence of leucite could be readily and reasonably explained either by incomplete crystallization or by the mass action of the abundant and complex alferic minerals and nephelite. Here, on the contrary, the majority of these abnormally leucitic rocks contain relatively large amounts

* A similar comparison has been undertaken by Lacroix (*Comptes rendues*, Vol. CCLI [1905], p. 1190), in discussing the granular leucitic sommaites of Monte Somma, though his norms are not calculated in the regular way, as he makes all the soda enter albite and does not assume the normative diopside molecule with $\text{CaSiO}_3 = (\text{Mg}, \text{Fe})\text{SiO}_3$.

of potash and small amounts of alferic minerals and often of nephelite, so that the mass action of these (which would also certainly tend to prevent the formation of leucite) may be neglected. Furthermore, some of these abnormally leucitic rocks are vitreous, so that the leucite has been formed in spite of their incomplete crystallization.

The explanation of the abnormality in the behavior of potash toward silica in these cases may be explained by two sets of factors, or rather by a combination of the two.

The tendency of the $\text{CaAl}_2\text{Si}_2\text{O}_8$ molecule to crystallize with that of $\text{NaAlSi}_3\text{O}_8$ as the mixed crystals of the soda-lime feldspars is well known. Pure anorthite is a rather rare feldspar, being met with, for the most part, only in rocks belonging to doleritic and perthitic ranges, gabbros and some basalts, though it occurs in a few rocks, andesites, vulcanites, and cinnabars, which are decidedly alkaline. But, speaking generally, the affinity of lime (in anorthite) for soda (in albite) seems to be very strong. Likewise purely potassic orthoclase and microcline are rarely met with, these minerals nearly always carrying very notable amounts of soda, as may be seen in the analyses given in Hintze's *Mineralogie*. On the other hand, both albite and anorthite, as well as their mixed crystals, the soda-lime feldspars, contain very little potash, the amount of this constituent in the analysis of the soda-lime feldspars being usually very small, and generally far less than the amounts of soda in orthoclase and microcline.

It is reasonable, therefore, to suppose that, under certain conditions, the affinity of lime and potash for soda to form feldspars may supersede the usually superior affinity of potash for silica, with the result that the $\text{CaAl}_2\text{Si}_2\text{O}_8$ molecules in the magma, and to a less extent those of KAlSi_3O_8 , will capture a certain amount of the soda present, forming soda-lime feldspar and soda-orthoclase. This soda will therefore bind three times as much silica as it would do if it entered into nephelite, leaving a correspondingly less quantity of this available for the potash, which would necessarily form leucite, if the amount of silica left available for it were less than enough to form only orthoclase.

Confining our attention for the moment to the soda-lime feldspars, it is evident that, on this hypothesis of the superior affinity of lime for soda, the abnormal formation of leucite would be aided by

the actual withdrawal of the amount of silica entering the albite molecule from the possibility of chemical combination with potash, that is, by the early crystallization of the sodic feldspars, at least in great part, thus bringing about the formation of leucite at a later stage. Such a withdrawal of silica by soda is rendered possible by the fact that labradorite has a greater tendency toward crystallization than have orthoclase and leucite,¹ as shown by the general truth of Rosenbusch's order of crystallization as far as regards labradorite, orthoclase, and leucite, which immediately concern us. Specific instances of this are presented by the Italian lavas, in the mantles of orthoclase about cores of anorthite and labradorite,² which have also been observed elsewhere, and in the inclusions of labradorite in large leucite phenocrysts.³

The objection may be raised to this explanation that the more calcic members of the soda-lime feldspar series, those with more anorthite than Ab_1An_1 , contain less silica than does leucite, and that, furthermore, it is precisely these more calcic members, especially labradorite, which are most apt to occur in connection with leucite, as is shown in the case of the Italian leucitic rocks. It might therefore seem to follow that the early crystallization of labradorite (Ab_1An_2), with a silica percentage of only 51.4 less than that of either leucite or orthoclase, would bring about in the remaining portion of the magma an increase of the silica percentage relative to that of potash, so that the early separation of labradorite ought to tend to prevent, rather than induce, the crystallization of leucite. Such an objection, however, leaves out of account the relations of the soda to the silica, and overlooks the fact that in entering albite molecules at an early stage of the crystallization it binds more silica than it would do if it were not thus removed and crystallized later as nephelite.

From the usually late crystallization of the alkali-feldspars it

¹ Cf. C. Doelter, *Petrogenesis* (1906), p. 136.

² H. S. Washington, *Journal of Geology*, Vol. IV (1896), p. 549; *The Roman Comagmatic Region* (1906), p. 30.

³ H. S. Washington, *The Roman Comagmatic Region* (1906), pp. 34, 91. Cf. E. Hussak, *Neues Jahrbuch* (1890), Vol. I, p. 168. It may be mentioned that labradorite is not listed as an inclusion in leucite by either Rosenbusch (*Mikroskopische Physiographie*, Vol. I, second half [1905], p. 32) or Iddings (*Rock Minerals* [1906], p. 242).

would seem that the influence of the binding of silica by soda in the formation of soda-orthoclase would be felt chiefly in peralkalic rocks, or, in more calcic ones, after the formation of labradorite had ceased, at least in great part. In the latter case its influence is probably comparatively slight, though in peralkalic rocks the crystallization of the alkali-feldspar and leucite is apt to be partially synchronous, so that it would be felt more strongly in these and would very materially tend to favor the formation of leucite.

In the preceding explanation it has been assumed to be a case of relative affinities, that of potash for silica and of lime and potash for soda. But it is clear that such questions of affinity may be disregarded and the result considered merely as dependent on the relative tendency toward crystallization of the several minerals involved, especially labradorite (or other soda-lime feldspars), orthoclase, and leucite. The effect would be the same in either case in influencing the formation of leucite.

Another mineral which may enter into the problem, and which would strongly influence the formation of leucite in certain cases, is analcite. This contains twice as much silica as does nephelite, and its crystallization would abstract silica from the magma, analogously to the crystallization of albite, though not to the same extent. Analcite contains two molecules of water, so that its formation can take place only when the molten magma contains water and under peculiar physical conditions. But that its presence may explain the formation of abnormative leucite in some rocks has been clearly shown by Pirsson.¹

The presence of alferic minerals has been disregarded as yet, since the amount of these in the exceptional rocks now under consideration is usually not very large. But a slight consideration of their characters and the relations of norm and mode will show that the influence of the early crystallization of these is also favorable to the development of leucite by abstracting from the magma an abnormative amount of silica. Considering augite alone, which is the alferic mineral most commonly met with in connection with leucite, the study of the relations of the norms and modes, as in the Italian

¹ L. V. Pirsson, *Bulletin No. 237*, U. S. Geological Survey (1905), pp. 11, 170.

rocks, shows that it is largely composed of the normative diopside. With this there enters also a smaller amount of the normative anorthite to furnish the alumina, and of normative magnetite to furnish the ferric oxide, both of which are present in the augite. To satisfy the demands of the normal augite formula, which may be stated as $m\text{Ca}(\text{Mg},\text{Fe})\text{Si}_2\text{O}_6 + n(\text{Mg},\text{Fe})(\text{Al},\text{Fe})_2\text{SiO}_6$, ferrous oxide and magnesia must be supplied from normative olivine, which will take up as much silica again as it contains to form a metasilicate molecule. The ferrous oxide of the normative magnetite will also demand its equivalent of silica to conform to the augite formula. Such, at least, was the set of readjustments which were found to be demanded in the case of the Italian volcanic rocks, the augite of which had been analyzed, and it is probable that the same or a very similar set would hold good in others. It will be seen that these readjustments are in the direction of the abstraction of silica from the magma by the early crystallization of augite, so that, while they may be slight in these rocks which are persalanes or dosalanes, yet the tendency of the crystallization of augite from a magma would be to favor the later formation of leucite. The influence of the early crystallization of either hornblende or biotite would be quite analogous; but, as they seldom occur in connection with leucite, they need not be discussed.

Examining the modes of the abnormally leucitic rocks plotted on Plate II, it will be found that the great majority of them (belonging to domalkalic or alkalicalcic rangs) carry considerable soda-lime feldspar, much of which has crystallized prior to the leucite, so far as may be gathered from the published descriptions, and as may be inferred from the usual order of crystallization. The sodic character of the alkali-feldspar is less easily demonstrable in most cases, but in the Italian rocks studied by me it was shown to be invariably decidedly sodic, ranging from Or_3Ab_1 to Or_1Ab_2 in the modally leucitic rocks, the composition in most cases being about Or_1Ab_1 , and from Or_6Ab_1 to Or_8Ab_9 in those free from leucite, the average composition being about Or_2Ab_1 . The more highly sodic character of the alkali-feldspars in the modally leucitic rocks is thus quite marked. This is perhaps best seen in the case of two arsal monzonoses. That from Poggio Cavaliere contains no modal leucite, and its alkali-feldspar has the composition Or_5Ab_1 ; while that of L'Arso contains

about 2 per cent. of leucite, and its alkali-feldspar is Or_4Ab_3 ; both rocks being chemically closely alike.¹

It should, of course, be possible to test this theoretical withdrawal of silica by the crystallization of soda-lime feldspar and soda-orthoclase by calculation based on the modes of actual rocks. The data necessary for this would be an exact knowledge of the order of crystallization, both qualitatively and quantitatively, and the compositions of the several modal minerals. It is clear that the former would be practically almost unattainable, owing to the difficulty of deciding the relative periods in many cases, and especially on account of the simultaneous crystallization of many of the minerals.

An attempt was made, however, on several of the Italian leucitic rocks, the modes of which have been quite exactly estimated. It was assumed that all the femic and alferic minerals, the ores, augite, and olivine, as well as all the soda-lime feldspar, had crystallized before that of the soda-orthoclase, leucite, and nephelite had begun. This, of course, may or may not be in accordance with the facts, but no definite, quantitative estimate of the relations was possible in any case. Unfortunately the composition of the alkali-feldspar was also unknown, and would have been almost impossible to determine in any case, as an analysis of the orthoclase phenocrysts would not necessarily indicate that of the more numerous groundmass feldspar laths, which cannot be separated mechanically and satisfactorily from the other constituents, owing to their small size and intimate juxtaposition.

Even though, on this basis, the calculations resolved themselves largely into working out backward the norm from the estimated mode, yet the fact that the amounts of some of the minerals, especially the leucite, had been estimated physically, and the composition of the soda-lime feldspar had been determined optically, gives them some weight. It would take up too much space to give the details here, but it may be stated that the results were fully confirmatory of the view that the early crystallization of soda-lime feldspars and of soda-

¹ *The Roman Comagmatic Region* (1906), pp. 75, 77. The determination of the composition of the Arso feldspar here, based partly on Rosiwal estimates of the amounts of leucite, augite, and olivine, and partly by readjustments of the other constituents, agrees well with that determined chemically by Fuchs (*T. M. P. M.* [1872], p. 233), who gives figures yielding $\text{Or}_{10}\text{Ab}_7$. The Poggio Cavaliere feldspar has not yet been analyzed.

orthoclase diminish the silica in the magma relatively to potash, and hence favor the crystallization of leucite. This was found to be true of soda-lime feldspar alone, as the portion of the magma remaining after the abstraction of the constituents of the minerals mentioned above, and neglecting the presence of albite in the alkali-feldspar, always yielded a greater amount of normative nephelite than that shown by the rock, thus proving that silica had been abstracted. And, naturally, the effect was still more marked if soda was assumed to go into the alkali-feldspar prior to the crystallization of leucite, the amount of this calculated from the composition of the last portion of the magma being the same as that determined in the mode, even if none is present in the norm, of the rock.

It will be observed that this favorable influence of the crystallization of soda-lime feldspars on the formation of leucite, consequent on the presence of considerable salic lime in the magma, is apparently at variance with the theoretical conclusion reached previously (p. 277), and based on the relative sizes of the leucitic areas, that the presence of anorthite should tend to lessen the probability of the presence of leucite. But it must be remembered that this was based only on a consideration of ideal norms, and that the influence of anorthite in forcing the soda to take up extra silica to form the modal albite molecule was disregarded.

It may also be pointed out that this action of the anorthite molecule offers a satisfactory explanation of the fact, noted by Zirkel and mentioned above (p. 258), that leucite is more often found in combination with plagioclase than with orthoclase.

On this assumption, the tendency to the formation of abnormative leucite will increase with the potash content of the magma, since the ratio of potash to silica will increase in the last portions to crystallize, and also, especially when potash is not very high, with its richness in salic lime and in soda, since the chemical composition will then be favorable to the formation of soda-lime feldspars. In conformity with these conclusions we have already noted the fact that the loci of these abnormative rocks are apt to fall rather near their respective leucitic areas, and that they are apt to contain the more leucite the nearer they approach these—that is, the higher they are in potash. It will also be noted that those rocks in which abnorma-

tive leucite is an accessory are quite calcic, belonging to the second and third rangs.

The influence of this factor just discussed is also seen in those rocks which carry both normative and modal leucite. In all of these, with one exception, where the mode has been adequately estimated, as in the Italian lavas, the amount of modal leucite surpasses that in the norm, so that a considerable portion of it is really abnormative. The exception is the missourite,¹ in which the amount of modal leucite is less than that in the norm, the difference being attributable to the formation of some biotite under the intrusive conditions.

On a previous page (371) it was suggested that the supersession of the affinity of lime and potash for soda over that of potash for silica could take place "under certain conditions." An idea of what these conditions may be is furnished by the long-recognized fact that leucite is characteristically a mineral of effusive igneous rocks. That it sometimes occurs in intrusive bodies is now well established by occurrences in Montana, Arkansas, and Brazil. It may be noted, as bearing on the problem, that there is only one known intrusive rock, missourite, in which purely potassic and unaltered leucite is found. In the others, as the fergusonite and leucite-shonkinite of Montana,² and the leucite-syenites and leucite-tinguaites of Brazil and Arkansas, the "leucites" are really pseudo-leucite, a mixture of alkali-feldspars and nephelite.³

But such occurrences of leucite are quite exceptional, and the generally recognized law may still be considered to hold good, that conditions which control during the solidification of effusive rocks favor the formation of leucite, while those obtaining in intrusive bodies tend to prevent it, the chemical composition of the magma admitting of the readjustments of silica necessary for the formation of leucite.

In this connection a few analyses will be worth quoting, which show these relations clearly. Others might be added,⁴ but those

¹ L. V. Pirsson, *Bulletin No. 237*, U. S. Geological Survey (1905), pp. 118, 119.

² L. V. Pirsson, *op. cit.*, pp. 106, 84.

³ Cf. Rosenbusch, *Mikroskopische Physiographie*, Vol. II, first half (1907), pp. 196, 617.

⁴ A similar comparison of analyses of leucitic and non-leucitic rocks of almost identical chemical composition is given by Lacroix (*Comptes Rendus*, Vol. CXLI [1905], p. 1190).

given below demonstrate how, of two magmas of practically identical chemical composition, the one which solidifies under intrusive conditions will be free from leucite, the potash going only into orthoclase in conformity with the norm, while in effusive flows leucite is apt to be formed, the amount of orthoclase shown in the norm being diminished modally and replaced by leucite, while the amount of normative albite is increased modally. Only the amounts of the more important constituents are given here.

	I	II	III	IV	V	VI	VII
SiO ₂	55.38	55.87	54.55	54.20	48.98	49.59	47.98
Al ₂ O ₃	23.74	20.85	19.07	19.38	12.29	14.51	13.34
Fe ₂ O ₃	0.63	2.34	2.41	3.83	2.88	3.51	4.09
FeO.....	1.26	1.10	3.12	2.14	5.77	5.53	4.24
MgO.....	0.81	0.48	1.98	1.35	9.19	6.17	7.01
CaO.....	0.67	3.07	3.15	2.15	9.65	9.04	9.32
Na ₂ O.....	5.29	4.81	7.67	8.01	2.22	3.52	3.51
K ₂ O.....	10.05	10.49	4.84	5.28	4.96	5.60	5.00

I. Grano-beemerose (nephelite-syenite). East Cape, Siberia. Washington, *American Journal of Science*, Vol. XIII (1902), p. 176.

II. Sabatinal beemerose (leucite-phonolite). Lake Bracciano, Italy. Washington, *Roman Comagmatic Region* (1906), p. 47.

III. Grano-laurdalose (laurdalite). Laugendal, Norway. Brögger, *Eruptivgesteine des Kristianiagebietes*, Vol. III (1899), p. 19.

IV. Phyro-laurdalose (leucite-rhombenporphyry). Kilimanjaro, East Africa, Finckh, *Rosenbusch Festschrift* (1906), p. 392.

V. Grano-shonkinose (shonkinite). Yogo Peak, Little Belt Mountains, Montana. Weied and Pirsson, *American Journal of Science*, Vol. L (1895), p. 474.

VI. Leucite-shonkinose (leucite-shonkinite). East Peak, Highwood Mountains, Montana. Pirsson, *Bulletin No. 237*, U. S. Geological Survey (1905), p. 108.

VII. Leucite-phyro-shonkinose (analcite-leucite-basalt). Highwood Peak. Highwood Mountains, Montana. Pirsson, *op. cit.* p. 168.

It may be thought that the slight differences observable in some of the constituents, especially in silica and potash, may account for the differences in the modes, at least in part. But study of the norms and the modes, so far as these latter are exactly ascertainable from the descriptions, shows indubitably that these chemical differences are entirely too slight to bring about the very great divergencies between the modes of the several pairs of rocks. The amounts of orthoclase and nephelite in the one, and of leucite and albite in the other member,

are entirely too great to be caused only by the slight variations in silica, soda, or potash shown by the analyses given above. In such magmas, therefore, whether leucite is formed or not must be held to depend upon some factor or factors extraneous to the magma itself; and these are to be looked for in the physical conditions which obtain during the solidification.

These conditions have been discussed by many petrographers, and it seems unnecessary to enlarge on them here, in view of the fact that the attitude of this paper is dominantly chemical, and because of the inadequacy of our knowledge of the physico-chemical properties of leucite, and other minerals, mentioned at the beginning of this paper (p. 259). It must suffice to say that the chief physico-chemical factors which under effusive conditions induce the formation of leucite in magmas chemically capable of permitting it seem to the writer to be:

a) The great tendency toward crystallization of the more calcic soda-lime feldspars and of leucite, that of nephelite being also considerable, but that of orthoclase being very slight under such conditions.

b) The relative stability of orthoclase, soda-lime feldspars, leucite, and nephelite, at different temperatures and pressures, the stability of the second and third of these being apparently greater under effusive conditions than those of the first and fourth. This is a matter which demands thorough experimental investigation.

c) The absence of mineralizers under effusive, and their presence under intrusive, conditions; the former permitting the magma to solidify and crystallize at a higher temperature, and so favor the formation of leucite, while the latter diminishes the viscosity, and thus permits the crystallization to proceed at a lower temperature and in a more fluid medium, which would favor the formation of orthoclase.

d) It is possible that, whether a molten magma is at rest or in motion, or whether it is subject or not to shocks, as of explosions of steam in a volcanic vent, may be of importance in inducing the crystallization of some minerals such as leucite; since it is known that tapping or agitation will frequently bring about the crystallization of an undercooled liquid.

The influence of other factors might be adduced, but the above must suffice. In any case, an appeal to them in explanation of the

formation of any mineral in igneous rocks must partake more or less of the nature of begging the question, in the absence of properly controlled physico-chemical experimental data. Any conclusions based on our present knowledge of the physico-chemical relations of minerals must rest on very insecure bases, and it were better not to attempt to draw them.

A few words may be devoted to the subsidiary point of the relative abundance of leucitic rocks. We have seen above (p. 271) that the size of the leucitic area is much smaller than those of the non-leucitic ones, the relations varying with the content in anorthite and femic molecules, but with a maximum of 21.61 per cent. of the whole in peralkalic and persalic magmas. It follows from this that the number of leucitic rocks actually to be observed should be considerably

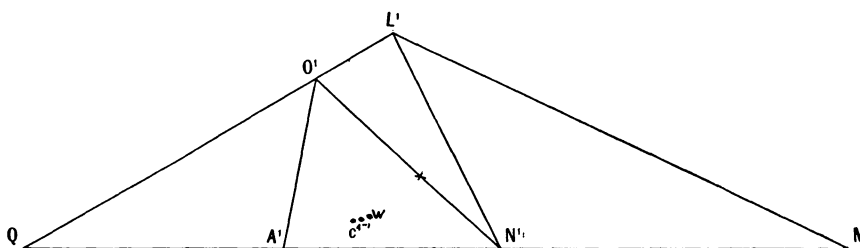


FIG. 1

less than the non-leucitic ones, though it does not follow that the actual relations must be exactly the theoretical ones. This would depend upon the general and the average compositions of all igneous rocks and the correspondence of these with the theoretical area QLM . As a matter of fact, we find that these do not correspond, the center of gravity of QLM falling at the point X (on the line $O'N'$), and the locus of the average rock well to the left of and below this, as shown in the adjoining figure. That is, igneous rocks, as they actually occur, are higher in silica and lower in potash than our theoretical magmas, of which amounts proportional to the theoretical limits of each are represented in our diagrams. It follows from this that leucitic rocks should actually be much more rarely met with than is indicated by the relative sizes of the various theoretical areas. That this is actually the case is shown by the following figures.

The normatively or modally leucitic rocks plotted in the diagram are distributed thus:

Those with normative and modal leucite	40
Those with normative but not modal leucite (vitreous)	21
Those with normative but not modal leucite (holocrystalline)	29
Those with modal but abnormative leucite	43

Reckoning the vitreous rocks with the first group, it will be seen that those which do not contain leucite when they should, and those which do contain it when they should not, pretty nearly balance each other, though the former are somewhat in the minority. They correspond, however, sufficiently well to allow the assumption for our purpose that the actual number of modally leucitic rocks corresponds with the number of those which should be leucitic according to our theory.

Now, taking the number of analyses to represent the relative amounts of the various kinds of igneous rocks, which is admittedly not strictly accurate, but sufficiently so for our purpose, and in any case being the only statistical basis we have, we find that all the analyses of igneous rocks to be found in Roth's *Tabellen* and in my *Collection*, as well as in the analyses published since and collected by me, number altogether 6,333. Of these, 278 are called leucitic, that is 4.41 per cent., while 6,055, or 95.59 per cent. are non-leucitic. While these figures are not of very great significance, on account of the unsatisfactory character of the data on which they are based, yet they are of some interest, and, taking into account the general characters and the average of igneous rocks, which would tend to lower very much the relative amounts of leucitic rocks, they are quite in harmony with our theory.

We may briefly summarize our comparison of the actual and the theoretical occurrence of leucite as follows:

The vast majority of igneous rocks conform to theory, based on the superior affinity of potash for silica, in that those whose norms are free from leucite are for the most part free from modal leucite, and the loci of nearly all of them fall outside their respective leucitic areas; while those whose norms are leucitic are very commonly modally leucitic also, and their loci all fall within their leucitic areas.

As regards modal leucite, there are certain exceptions which,

while not very numerous, are yet significant, and which may be referred to two kinds: those which are modally free from leucite, though they contain it in the norm, the abnormality being explicable, in part by the incomplete crystallization, and in part by the mass effect of the complex minerals present in abundance in these rocks, and their comparative paucity in potash; and those whose modes contain abnormative leucite, either showing none of this in the norm, or containing modally more than exists normatively, these cases being explicable by the early crystallization of soda-lime feldspars (due either to the superior affinity of lime for soda or to the great tendency toward crystallization of these feldspars), and of soda-orthoclase or analcite which may crystallize either prior to or at the same time as the leucite.

In both classes of exceptions the conditions of solidification seem to have a determining effect, those obtaining in effusive rocks favoring, and those in intrusive rocks deterring, the formation of leucite.

A few exceptions, which cannot be explained by any of the suppositions made above, remain to be discussed. The first is the so-called leucite-granite-porphyry of Brazil, described by Hussak,¹ which consists of large phenocrysts of pseudo-leucite in a fine-grained groundmass composed of orthoclase and quartz, thus apparently forming an exception to the otherwise invariable incompatibility of quartz and leucite. This highly anomalous occurrence is explained by Hussak (*loc. cit.*, p. 26) as the result of a "granophyric" magma breaking through a leucite-foyaite or leucite-tinguaite; and this explanation may reasonably be accepted as the true one.

The only other exceptions which need be discussed are the wyomingite and the orendites of the Leucite Hills (Nos. 104, 105, 106), which carry abundant modal leucite and whose loci fall within their leucitic area, though they do not show either leucite or nephelite in the norm, and even in one case have normative quartz. These rocks, furthermore, have an excess of alkalis over that needed for feldspar and acmite, resulting in the presence of sodium and potassium metasilicates in the norm. The peculiar features of these rocks have been discussed by Cross,² who shows that they cannot be due to errors of analysis,

¹ E. Hussak, *Neues Jahrbuch* (1900), Vol. I, p. 22.

² W. Cross, *American Journal of Science*, Vol. IV (1897), pp. 131-34.

and who leaves the discordance between their chemical and modal characters unexplained. In this condition we also are perforce compelled to leave them still, as study of the relations of norm and mode, and consideration of the presence of the phlogopite, but add to the difficulties of explanation. These rocks may well be considered as, chemically, the most remarkable and the least susceptible of correlation of any igneous rocks so far discovered.

GENERAL CONCLUSIONS

From the above discussions and comparisons we may draw certain general conclusions, both as to the affinity of the various bases in igneous rocks for silica and as to the formation of leucite, these conclusions being stated under the two separate heads.

Affinity for silica.—The assumption with which we started, that potash has a greater affinity for silica than has any of the other oxides, is amply substantiated, and may be considered as fully established, subject to certain modifications mentioned later.

Next to potash, soda has the most affinity for silica, the affinities of magnesia and ferrous oxide being considerably less, so that normative nephelite will take up silica before normative olivine.

While these relative affinities apply in the great majority of cases, and under most conditions, yet, in accordance with the general laws of chemical affinity and of mass action, they are susceptible of notable change under certain conditions, especially of temperature and pressure, and the presence of mineralizers, and may be in part superseded by the influence of the mass action of abundant complex molecules and the relative crystallizability of the minerals involved, the influence of the ready crystallization of soda-lime feldspars constituting the most notable case in point.

Soda and lime, as alumino-silicates, have a strong affinity for each other, as have soda and potash alumino-silicates, though to a somewhat less extent; and if lime and soda are present in sufficient amount in the magma, these affinities may supersede, at least partially, the usual greater affinity of potash for silica.

In the presence of water in the magma, and under certain conditions, the affinity of soda for silica may supersede that of potash, resulting in the formation of analcite and leucite.

These affinities must be regarded as acting in one direction only, that mentioned in the several cases above, since, were they reversed, the resulting modes would be quite incompatible in general with our observations.

Formation of leucite.—The formation of leucite is an unusual occurrence, and the number of leucitic rocks will always remain but a very small fraction of all known igneous rocks.

The formation of leucite is, in general, primarily dependent upon the chemical composition of the magma, subject, however, to the modifying influence of certain factors, such as physical conditions and the mass action of complex mineral molecules, to be mentioned later.

The chief chemical factors involved are the percentages of silica and of potash, and the ratio of soda to potash, but this last and the amounts of the other constituents are of subordinate importance. These statements are subject to the modifications mentioned in the preceding paragraph.

Leucite will not be formed in rocks with an excess of silica—that is, more than enough to saturate the bases completely and form the most highly silicated mineral molecules possible. It follows from this that leucite and quartz are incompatible and will not occur together.

As regards silica, rocks containing leucite may range between the silica percentage of orthoclase (64.75) as a maximum, down to the absence of silica as a minimum limiting value. The actual possible maximum will, however, depend upon the amount of anorthite and of femic molecules, all of these decreasing very markedly the possible amount of silica.

As regards potash, the limits lie between the percentage of leucite (21.56) as a maximum (though this may be conceivably exceeded owing to the existence of the kaliophilite molecule) and the disappearance of potash as a minimum. The actual maximum will depend upon the amounts of anorthite and of femic molecules present, as in the preceding case.

The greatest range in silica consistent with the formation of leucite, and consequently the greatest probability of its formation, for any given percentage of anorthite and femic molecules, will be found when the

percentage of potash is that of a mixture of orthoclase with the given amount of the other constituents mentioned. From this most favorable maximum the range in silica, and consequently the probability of the formation of leucite, will diminish rather slowly with decreasing potash, while, at the same time, the probability of the rock being non-leucitic, as well as the possible number of rocks, will increase. On the other hand, only leucitic rocks can be expected with higher potash than this amount, but their range in silica and the probability of their occurrence will diminish rapidly with increasing potash.

Similarly, the greatest range in potash, and hence the greatest probability of the formation of leucite, will be found when the silica percentage is that of a mixture of leucite with the given amount of anorthite and femic molecules. From this most favorable maximum, the range in potash and the probability of the formation of leucite will diminish slowly as silica decreases, but more rapidly as silica increases.

While the maximum ranges of silica and of potash, expressed in percentages of the whole rock are about the same (for example, 12.54 and 12.00 respectively in peralkalic persalanes), yet relatively to the amounts of each present the possible range of potash is much greater than that of silica. So that we may expect to find the potash range of leucitic rocks very great, while that of silica will be comparatively small.

If leucite is present in the norm of a rock, it should also be present in the mode, provided that the crystallization is complete and the magma has solidified under effusive conditions. The formation of leucite in such normatively leucitic magmas may, however, be, and often is, wholly prevented by the presence of femic constituents in large amounts, giving rise to the modal presence of alferic minerals with highly complex constituents, such as biotite, hornblende, augite, or melilite, the potash being incorporated in these by their mass action. The presence of abundant soda may also prevent the formation of leucite by the incorporation of the potash in the complex nephelite molecule. Both of these effects are most apt to occur if the rock has solidified under intrusive conditions. Leucite should therefore be rarely met with in highly femic rocks, as the dofemanes and perfemanes, as well as in those which are highly sodic, both of these characters implying, of course, that the magma is not very potassic.

If leucite is not present in the norm, we should not expect to find it in the mode, especially if the rock is intrusive. But if the magma has solidified under effusive conditions, is rather low in silica and high in potash, and if it contains considerable salic lime and soda, leucite is apt to form. The crystallization of soda-lime feldspar, and less often of soda-orthoclase or analcite, is a prerequisite to the formation of leucite in such cases, and the tendency to its formation will be the greater the higher the rock is in potash, though the presence of considerable salic lime and soda may bring about the crystallization of leucite even if the amount of potash is small. It follows from this that soda-lime feldspars will be frequent concomitants of leucite; and this we find to be actually the case.

The presence in the norm of such mineral molecules as nephelite or olivine, which are not fully silicated, is a necessary condition for the formation of modal leucite, if there is none in the norm; that is, the magma must be deficient in silica. Of these minerals, nephelite is the most important, modal leucite being usually formed by a readjustment of silica involving the taking-up of silica by normative nephelite to form modal albite, which usually enters the soda-lime feldspars. Olivine is much less prone to take silica away from potash, but may do so. The crystallization of alferic minerals, especially augite, also favors the formation of leucite by abstracting silica from the magma.

Effusive conditions tend to favor, and intrusive conditions tend to check or wholly prevent, the formation of leucite in magmas from which it is chemically possible for it to form. It is because of this that augite occurs more often with leucite than do hornblende or biotite. In general, the leucitoid mineral formed under intrusive conditions is the so-called pseudo-leucite, which contains a very considerable amount of soda, and which consists of an intimate mixture of orthoclase and nephelite.

Miscellaneous conclusions.—The preceding discussions emphasize the possibility of the formation of widely diverse modes from chemically identical magmas, these divergencies of the mode from the norm or from each other taking place in different directions and to varying degrees, from practically complete agreement with the norm to the greatest possible divergence from it, though these last are less

common than cases where the norm and mode correspond in many particulars.

The readjustments shown to be possible in the case of the leucitic rocks indicate that the mineral molecules probably do not exist as such in the molten magma, but that they are dissociated into simpler molecular groupings, or their constituent oxides or ions, capable of reacting differently among themselves according to the conditions of solidification.

The facts brought out in the preceding discussion do not seem to favor the theory of eutectic mixtures in explaining the crystallization of rocks, at least so far as the leucitic rocks are concerned.

There is indicated the possibility that pseudo-leucite is not a pseudomorph after original leucite, but that it replaces a distinct, soda-potash mineral, as yet unknown, which was not stable under the conditions following its period of crystallization. The evidence in regard to this will be discussed subsequently, in connection with some Sardinian leucitic lavas.

APPENDIX II
LIST OF ROCKS PLOTTED

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
1	I.5.1.3	.1.031	.071	.681	NoMo	Trachyte	Ischia	R.C.R. 20	Effusive
2	I.5.1.3	.097	.076	.673	NoMo	Trachyte	Mte. Cuma	R.C.R. 23	Effusive
3	I.5.1.3	.1.006	.078	.696	NoMo	Trachyte	Mte. Nuovo	R.C.R. 23	Effusive
4	I.5.1.3	.097	.097	.672	NoMo	Trachyte	Mte. Vico	R.C.R. 23	Effusive
5	I.5.1.3	.1.027	.081	.678	NoMo	Trachyte-obsidian	Ischia	R.C.R. 28	Effusive
6	I.5.2.2	.068	.095	.674	NoMo	Vulsinite	Bolsena	R.C.R. 31	Effusive
7	I.5.2.2	.060	.093	.675	NoMo	Vulsinite	Astroni	R.C.R. 31	Effusive
8	I.5.2.2	.058	.089	.671	NoMo	Vulsinite	Astroni	R.C.R. 31	Effusive
9	I.5.2.2	.036	.112	.674	NoMI	Leucite-trachyte	Mte. Vico	R.C.R. 36	Effusive
10	I.5.2.2	.020	.102	.665	NoMI	Leucite-trachyte	Mte. Vico	R.C.R. 36	Effusive
11	I.5.2.2	.104	.094	.711	NoMI	Leucite-granite-porphry	Brazil	W. T. 199	Mixture of rocks
12	I.5.2.3	.060	.093	.686	NoMo	Vulsinite	Astroni	R.C.R. 43	Effusive
13	I.5.2.3	.018	.093	.676	NoMI	Leucite-trachyte	Proceno	R.C.R. 43	Effusive
14	I.5.3.2	.089	.074	.716	NoMo	Augite-syenite	British Guiana	W.T. 205	Intrusive
15	I.6.1.3	.031	.112	.687	NoMI	Leucite-phonolite	Bracciano	R.C.R. 47	Effusive
16	I.6.1.3	.093	.101	.683	NoMo	Nephelite-syenite	Beemerville	W.T. 207	Intrusive
17	I.6.1.3	.023	.107	.656	NoMo	Nephelite-syenite	Siberia	A.J.S., XIII, 1902, 176	Intrusive
18	I.6.1.3	.082	.117	.690	NoMo	Leucite-tinguaite-vitrophire	Portugal	W.T. 207	Vitreous; no leucite
19	I.6.1.3	.020	.089	.676	NoMI	Leucite-phonolite	Eifel	W.T. 207	Effusive
20	I.6.1.4	.081	.064	.701	NoMI	Leucite-phonolite	Eifel	W.T. 211	Effusive
21	I.6.2.4	.004	.043	.660	NoMI	Leucite (?) microsyenite	Madagascar	M.M. 205	Leucite doubtful; intrusive
22	I.7.1.3	.838	.120	.691	NIMI	Leucite-tephrite	Tavolato	R.C.R. 51	Effusive
23	I.7.1.3	.892	.094	.695	NoMo	Nephelite-syenite	Magnet Cove	W.T. 215	Intrusive
24	II.4.3.3	.990	.056	.671	NoMo	Biotite-latte	Mte. Cimino	R.C.R. 56	Normative quartz
25	II.5.1.2	.931	.099	.634	NoMo	Syenite	New So. Wales		Intrusive

APPENDIX II—Continued

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
26	II.5.1.2	.067	.107	.698	NoMo	Tinguaite	Highwood Mts.	Bull. 237, 128	Intrusive
27	II.5.2.2	.055	.097	.683	NoMo	Vulsinite	Mte. Vico	R.C.R. 59	Effusive
28	II.5.2.2	.024	.071	.709	NoMo	Ciminite	Mte. Cimino	R.C.R. 63	Effusive
29	II.5.2.2	.055	.068	.742	NoMo	Ciminite	Mte. Cimino	R.C.R. 63	Effusive
30	II.5.2.2	.031	.094	.669	NoMI	Leucite-trachyte	Bagnorea	R.C.R. 67	Effusive
31	II.5.2.2	.020	.090	.678	NoMI	Leucite-trachyte	Mte. Vico	R.C.R. 67	Effusive
32	II.5.2.2	.869	.077	.700	NoMI	Leucite-tephrite	Mte. Vico	R.C.R. 72	Effusive
33	II.5.2.2	.851	.077	.647	NoMo	Durbachite	Durbach	W.T. 255	Intrusive; biotite
34	II.5.2.2	.940	.083	.722	NoMo	Selagite	Mte. Catini	W.T. 255	Effusive; biotite
35	II.5.2.3	.920	.081	.690	NoMo	Vulsinite	Mte. Vico	R.C.R. 75	Effusive
36	II.5.2.3	.946	.063	.682	NoMI	Vulsinite	Ischia	R.C.R. 75	Effusive
37	II.5.2.3	.912	.073	.683	NoMI	Vulsinite	Astroni	R.C.R. 75	Effusive
38	II.5.2.5	.740	.068	.563	NoMI	Leucite-basanite	Mte. Ferru	Unpublished	Effusive
39	II.5.3.2	.873	.080	.661	NoMI	Leucite-tephrite	Mte. Vico	R.C.R. 80	Effusive
40	II.5.3.2	.848	.077	.672	NoMI	Leucite-trachyte	Rocca Monfina	R.C.R. 83	Effusive
41	II.5.3.2	.854	.070	.695	NoMI	Leucite-tephrite	Toscanelia	R.C.R. 86	Effusive
42	II.5.3.2	.847	.074	.672	NoMo	Minette	Plauren	W.T. 265	Intrusive; biotite
43	II.5.3.2	.837	.092	.683	NoMI	Sommaite	Mte. Somma	C.R. CXXI, 1190	Intrusive (?)
44	II.5.3.3	.928	.047	.724	NoMo	Biotite-laitite	Rocca Monfina	R.C.R. 88	Effusive; normative quartz
45	II.5.3.3	.882	.051	.659	NoMI	Leucite-banakitite	Yell. Nat. Park	W.T. 267	Effusive
46	II.5.3.3	.875	.039	.674	NoMI	Leucite-shoshonite	Yell. Nat. Park	W.T. 267	Effusive; leucite doubtful
47	II.5.3.3	.859	.044	.642	NoMI	Leucite-banakitite	Yell. Nat. Park	W.T. 267	Effusive
48	II.5.3.3	.829	.033	.666	NoMI	Leucite-tephrite	Bohemia	W.T. 271	Effusive
49	II.5.3.3	.861	.052	.671	NoMI	Sommaite	Mte. Somma	C.R. CLXI, 1190	Intrusive (?)
50	II.5.3.3	.835	.045	.678	NoMI	Sommaite	Mte. Somma	C.R. CLXI, 1190	Intrusive (?)
51	II.5.3.4	.872	.029	.675	NoMI	Leucite-tephrite	Bohemia	W.T. 283	Effusive
52	II.6.1.1	.909	.114	.804	NIMI	Wyomingite	Leucite Hills	W.R.T. 51	Effusive
53	II.6.1.2	.863	.081	.701	NoMI	Fergusonite	Highwood Mts.	Bull. 237, 86	Intrusive; pseudo-leucite
54	II.6.1.3	.885	.089	.698	NoMo	Foyaite	Magnet Cove	W.T. 293	Intrusive
55	II.6.1.3	.882	.084	.682	NoMI	Leucite-tinguaite	Magnet Cove	W.T. 293	Intrusive; pseudo-leucite
56	II.6.1.3	.961	.098	.724	NoMo	Tinguaite	Judith Mts.	W.T. 293	Intrusive

APPENDIX II—Continued

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
57	II.6.1.3	.958	.100	.738	NoMo	Tinguaite	Bearpaw Mts.	W.T. 295	Intrusive
58	II.6.1.3	.866	.082	.686	NoMo	Syenite-porphyr	Highwood Mts.	Bull. 237, 139	Intrusive
59	II.6.1.3	.934	.093	.733	NoMo	Nephelite-syenite	Brazil	W.T. 295	Intrusive
60	II.6.1.3	.919	.074	.630	NoMo	Syenite	New South Wales	P.R.S.N.S.W. XXXVII, 341	Intrusive
61	II.6.1.4	.901	.072	.701	NoMI	Leucite-tinguaite	Magnet Cove	W.T. 295	Intrusive; pseudo-leucite
62	II.6.1.4	.903	.056	.649	NoMI	Leucite-porphyr	Kilimanjaro	R.F. 392	Effusive
63	II.6.1.4	.891	.062	.662	NoMI	Leucite-porphyr	Kilimanjaro	R.F. 392	Effusive
64	II.6.2.2	.914	.091	.688	NoMI	Leucite-tephrite	Mte. Vico	R.C.R. 92	Effusive
65	II.6.2.2	.853	.113	.670	NIMI	Leucite-tephrite	Rocca Monfina	R.C.R. 92	Effusive
66	II.6.2.2	.845	.100	.675	NIMI	Leucite-tephrite	Bracciano	R.C.R. 97	Effusive
67	II.6.2.2	.839	.100	.676	NIMI	Leucite-tephrite	Bracciano	R.C.R. 97	Effusive
68	II.6.2.2	.838	.080	.680	NIMI	Leucite-tephrite	Orvieto	R.C.R. 101	Effusive
69	II.6.2.3	.856	.071	.679	NoMo	Leucite-tephrite	Magnet Cove	W.T. 297	Intrusive
70	II.6.2.3	.828	.053	.684	NoMo	Nephelite-felsite	Magnet Cove	W.T. 297	Intrusive
71	II.6.2.3	.868	.085	.716	NoMo	Covite	Highwood Mts.	Bull. 237, 92	Intrusive
72	II.6.2.3	.832	.056	.660	NoMo	Syenite	Highwood Mts.	Bull. 237, 96	Intrusive
73	II.6.2.3	.833	.091	.651	NoMo	Syenite	Highwood Mts.	Bull. 237, 92	Intrusive
74	II.6.2.4	.832	.040	.704	NoMI	Leucite-kulaite	Kula	W.T. 299	Effusive
75	II.6.2.4	.806	.042	.685	NoMo	Kulaite	Kula	W.T. 299	Effusive
76	II.6.2.5	.748	.058	.610	NoMo	Leucite-basanite	Mte. Ferru	Unpublished	Effusive
77	II.6.3.2	.821	.056	.702	NoMI	Leucite-basalt	Ermiti	W.T. 301	Effusive
78	II.7.1.3	.866	.104	.725	NIMI	Leucite-tinguaite	Bearpaw Mts.	W.T. 303	Intrusive; pseudo-leucite
79	II.7.1.3	.885	.073	.736	NoMo	Tinguaite	Brazil	W.T. 303	Intrusive
80	II.7.1.3	.869	.086	.711	NIMI	Leucitophyre	Brazil	W.T. 303	Effusive
81	II.7.1.3	.833	.088	.681	NIMI	Leucite-tinguaite	Beemerville	R.C.R. 104	Intrusive; pseudo-leucite(?)
82	II.7.2.2	.794	.080	.721	NIMI	Leucite-tephrite	Vesuvius	R.C.R. 109	Effusive
83	II.7.2.2	.798	.087	.684	NIMI	Leucitite	Bracciano	R.C.R. 113	Effusive
84	II.7.2.2	.787	.081	.698	NIMI	Leucitite	Alban Hills	R.C.R. 116	Effusive; vitreous
85	II.7.2.2	.802	.084	.672	NIMI	Leucite-tephrite	Vesuvius	R.C.R. 118	Effusive
86	II.7.2.2	.795	.081	.702	NIMI	Leucite-tephrite	Vesuvius		Effusive

APPENDIX II—Continued

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
87	II.7.2.2	.817	.096	.693	NiMI	Leucite-tephrite	Vesuvius	W.T. 305	Effusive
88	II.7.2.4	.708	.049	.669	NiMI	Haunophyre	Mt. Vulture	W.T. 305	Effusive
89	II.7.3.2	.811	.069	.643	NiMI	Leucitophyre	Vesuvius	W.R.T. 53	Effusive
90	II.7.3.3	.790	.063	.716	NiMI	Leucite-tephrite	Rocca Monfina	W.T. 305	Effusive
91	II.7.3.3	.786	.070	.697	NiMI	Leucitophyre	Vesuvius	W.R.T. 53	Effusive
92	II.7.3.4	.651	.019	.652	NiMo	Nephelinite	Rhöngebirge	W.T. 305	Effusive; vitreous
93	II.7.3.4	.651	.027	.630	NiMo	Nephelite-basalt	Rhöngebirge	W.T. 305	Effusive; vitreous
94	II.8.1.4	.804	.062	.741	NiMo	Biotite-ijolite	Odenwald	W.R.T. 53	Effusive; vitreous
95	II.8.2.4	.635	.023	.615	NiMo	Haunophyre	Magnet Cove	W.T. 307	Intrusive; biotite
96	II.8.2.4	.659	.060	.600	NiMI	Leucite-syenite	Mt. Vulture	Unpublished	Effusive
97	II.9.1.3	.740	.087	.664	NiMI	Nephelite-porphyre	Magnet Cove	W.T. 307	Intrusive; pseudo-leucite
98	II.9.1.3	.761	.074	.690	NiMo	Leucite	Kola	W.T. 307	Intrusive
99	II.9.1.3	.775	.072	.697	NiMI	Urtite	Kamerun	W.T. 307	Effusive
100	II.9.1.4	.758	.045	.731	NiMo	Urtite	Kola	W.T. 307	Intrusive
101	II.9.1.4	.757	.036	.710	NiMo	Urtite	Kola	W.T. 307	Intrusive
102	II.9.1.4	.755	.037	.728	NiMo	Urtite	Kola	W.T. 307	Intrusive
103	II.9.1.4	.717	.032	.699	NiMo	Ijolite	Kola	W.T. 307	Intrusive
104	III.5.1.1	.903	.126	.686	NoMI	Orendite	Leucite Hills	W.T. 313	Effusive; biotite
105	III.5.1.1	.901	.125	.671	NoMI	Orendite	Leucite Hills	W.T. 313	Effusive; normative quartz
106	III.5.1.1	.893	.119	.661	NoMI	Wyomingite	Leucite Hills	W.T. 313	Effusive; biotite
107	III.5.1.1	.846	.079	.659	NoMI	Jumillite	Murcia	R.F. 290	Effusive
108	III.5.1.2	.814	.061	.517	NoMI	Jumillite	Murcia	R.F. 290	Effusive
109	III.5.2.2	.840	.080	.672	NoMo	Syenitic-lamprophyre	Colorado	J.G. XIV, 168	Intrusive
110	III.5.2.2	.871	.064	.681	NoMo	Syenite-porphyre	Maine	J.G. XIV, 179	Intrusive
111	III.5.2.3	.789	.040	.683	NoMI	Leucite-absarokite	Yell. Nat. Park	W.T. 313	Effusive
112	III.5.2.4	.781	.028	.606	NoMI	Leucite-tephrite	Bohemia	W.T. 315	Effusive; normative quartz
113	III.5.3.4	.788	.023	.679	NoMI	Leucite-absarokite	Yell. Nat. Park	W.T. 321	Effusive
114	III.6.1.1	.837	.104	.682	NiMI	Wyomingite	Leucite Hills	W.T. 339	Effusive
115	III.6.1.3	.833	.034	.708	NoMo	Shonkinit	Bearpaw Mts.	W.T. 339	Intrusive
116	III.6.2.3	.827	.060	.724	NiMI	Leucite-shonkinit	Highwood Mts.	Bull. 237, 108	Intrusive; pseudo-leucite
117	III.6.2.3	.800	.054	.675	NoMI	Leucite-basalt	Highwood Mts.	Bull. 237, 168	Effusive

APPENDIX II—Continued

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
118	III.6.2.3	.779	.040	.602	NoMo	Shonkinit	Highwood Mts.	Bull. 237, 102	Intrusive
119	III.6.2.3	.816	.053	.602	NoMo	Shonkinit	Little Belt Mts.	W.T. 341	Intrusive
120	III.6.2.3	.828	.059	.602	NoMI	Leucitophyre	Persia	W.T. 341	Effusive
121	III.6.2.4	.731	.031	.609	NoMI	Leucite-basanite	Kaiserstuhl	W.T. 341	Effusive
122	III.6.2.4	.797	.043	.670	NoMI	Leucite-tephrite	Bohemia	W.T. 343	Effusive
123	III.6.3.2	.794	.051	.716	NIMI	Leucite-tephrite	Mte. Somma	C.R. CXLI, 1192	Effusive
124	III.6.3.3	.708	.029	.669	NIMo	Monchiquite	Castle Mts.	W.T. 343	Intrusive; glass or analcite
125	III.6.3.4	.632	.022	.601	NIMo	Hornblende	Norway	W.T. 345	Intrusive
126	III.6.3.4	.656	.019	.633	NIMI	Leucite-monchiquite	New South Wales	R.G.S.N.S.W. VIII, 50	Effusive
127	III.6.4.3	.643	.015	.631	NIMo	Ariegite	Pyrenees	W.T. 347	Intrusive
128	III.6.4.3	.686	.017	.671	NIMI	Leucite-basalt	Vogelsberg	W.T. 347	Effusive
129	III.6.4.3	.644	.007	.636	NIMo	Limburgite	Cape Verde Is.	W.T. 347	Effusive; vitreous
130	III.7.1.3	.798	.056	.700	NIMo	Malignite	Ontario	W.T. 347	Intrusive
131	III.7.2.2	.790	.073	.714	NIMI	Leucitite	Lake Bolsena	R.C.R. 124	Effusive
132	III.7.2.3	.767	.062	.665	NIMI	Minette	Highwood Mts.	Bull. 237, 144	Intrusive; biotite
133	III.7.2.4	.665	.038	.633	NIMo	Nephelite-basalt	Löbauerberg	W.T. 349	Effusive; vitreous
134	III.7.2.4	.668	.035	.611	NIMI	Leucite-nephelinite	Kamerun	W.T. 349	Effusive
135	III.7.2.4	.666	.038	.614	NIMI	Leucite-nephelinite	Kamerun	W.T. 349	Effusive
136	III.7.2.4	.655	.016	.548	NoMo	Haunophyre	Kamerun	W.T. 349	Effusive
137	III.7.2.4	.711	.016	.693	NIMo	Basalt	Cape Verde Is.	W.R.T. 59	Effusive
138	III.7.2.4	.671	.016	.623	NoMI	Leucite-monchiquite	New South Wales	R.G.S.N.S.W. VII, 302	Effusive
139	III.7.3.2	.748	.039	.725	NIMI	Leucite-basanite	Lake Bolsena	R.C.R. 127	Effusive
140	III.7.3.2	.667	.032	.576	NIMo	Ouachitite	Hot Springs	W.T. 349	Intrusive; biotite
141	III.7.3.4	.709	.023	.680	NIMo	Monchiquite	Orkney Is.	W.T. 351	Intrusive; vitreous
142	III.7.3.4	.720	.013	.701	NIMo	Nephelite-basalt	Hesse	W.T. 351	Effusive; vitreous
143	III.7.3.4	.695	.011	.671	NIMo	Basalt	Bohemia	W.T. 351	Effusive; vitreous
144	III.7.3.4	.656	.016	.638	NIMo	Nephelite-basalt	Bohemia	W.T. 351	Effusive; vitreous
145	III.7.3.4	.656	.036	.603	NIMo	Haunophyre	Kamerun	W.T. 351	Effusive; vitreous

APPENDIX II—Continued

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
146	III.7.3.4	.603	.019	.593	NiMo	Mellilite-basalt	Cape Colony	A.R.G.C.C.G.H. 1903, 51	Effusive; mellilite
147	III.7.3.4	.676	.021	.651	NiMo	Nephelite-basalt	Rosberg	W.R.T. 59	Effusive; vitreous(?)
148	III.7.3.5	.679	.006	.672	NiMo	Nephelite-basalt	Rhöngebirge	W.T. 351	Effusive; much nephelite
149	III.8.1.2	.775	.092	.657	NiMI	Leucitite	Bearpaw Mts.	W.T. 351	Effusive
150	III.8.1.2	.753	.074	.668	NiMI	Leucite-basalt	New South Wales	R.G.S.N.S.W. VII, 302	Effusive
151	III.8.2.2	.771	.068	.716	NiMI	Leucitite	Lake Bolsena	R.C.R. 131	Effusive
152	III.8.2.2	.771	.091	.687	NiMI	Leucitite	Ernici	R.C.R. 135	Effusive
153	III.8.2.2	.784	.080	.712	NiMI	Leucitite	Ernici	R.C.R. 135	Effusive
154	III.8.2.2	.767	.096	.676	NiMI	Leucitite	Alban Hills	R.C.R. 139	Effusive
155	III.8.2.2	.768	.055	.720	NiMI	Missourite	Highwood Mts.	Bull. 237, 117	Intrusive
156	III.8.2.3	.687	.038	.650	NiMo	Nephelinite	Laacher See	W.R.T. 59	Effusive; vitreous
157	III.8.2.3	.606	.039	.564	NiMo	Mellilite-basalt	Hegau	W.T. 351	Effusive; mellilite
158	III.8.2.4	.696	.042	.649	NiMo	Ijolite	Magnet Cove	W.T. 353	Intrusive
159	III.8.2.4	.649	.019	.629	NiMo	Biotite-ijolite	Magnet Cove	W.T. 353	Intrusive; biotite
160	III.8.2.4	.720	.043	.662	NiMo	Theralite	Crazy Mts	W.T. 353	Intrusive
161	III.8.2.4	.711	.038	.677	NiMI	Nephelite-basanite	Hesse	W.T. 353	Effusive; vitreous
162	III.8.2.4	.669	.040	.630	NiMI	Leucitic-nephelinite	Kamerun	W.T. 353	Effusive
163	III.8.2.4	.640	.026	.607	NiMI	Leucitic-nephelinite	Kamerun	W.T. 353	Effusive
164	III.8.2.4	.661	.033	.626	NiMo	Teschelinite	Cape Verde Is.	W.T. 353	Intrusive; biotite
165	III.8.2.4	.661	.033	.620	NiMo	Olivine-diabase	Cape Verde Is.	W.R.T. 59	Intrusive; vitreous(?)
166	III.8.2.5	.769	.010	.758	NiMo	Nephelinite (andesite)	Grenada	W.T. 353	Effusive; vitreous
167	III.9.1.2	.711	.085	.625	NiMo	Madupite	Leucite Hills	W.T. 353	Effusive; vitreous
168	III.9.1.4	.751	.031	.737	NiMo	Nephelinite	Odenwald	W.R.T. 61	Effusive; vitreous
169	III.9.1.4	.747	.039	.716	NiMo	Nephelinite	Odenwald	W.R.T. 61	Effusive; vitreous
170	III.9.1.4	.728	.030	.690	NiMo	Ijolite	Kola	W.T. 353	Intrusive
171	III.9.1.5	.701	.020	.684	NiMo	Ijolite	Kola	W.T. 353	Intrusive
172	IV.11.11	.701	.012	.691	NiMo	Limbürgite	Habichtswald	W.T. 355	Effusive; vitreous
173	IV.11.11	.714	.007	.719	NiMo	Olivine-basalt	Grenada	W.T. 355	Effusive; vitreous
174	IV.11.11	.789	.028	.695	NoMI	Jumillite	Murcia	R.F. 305	Effusive

APPENDIX II—Continued.

No.	Symbol	SiO ₂	K ₂ O	N	Norm and Mode	Name	Locality	Reference	Remarks
175	IV. ₂ ¹ ₁ ² ₃	.672	.012	.673	NiMo	Nephelite-basalt	Rhöngebirge	W.T. 357	Effusive; vitreous (?)
176	IV. ₂ ¹ ₁ ² ₂	.654	.006	.648	NiMo	Hornblende-peridotite	Pyrenees	W.T. 357	Intrusive
177	IV. ₂ ¹ ₁ ² ₂	.691	.079	.711	NiMi	Venanzite	Umbria	W.T. 357	Effusive
178	IV. ₂ ¹ ₁ ² ₂	.751	.009	.746	NiMo	Pyroxenite	Norway	W.T. 359	Intrusive
179	IV. ₂ ¹ ₁ ² ₂	.637	.024	.606	NiMo	Mellilite-basalt	Hegau	W.T. 359	Effusive
180	IV. ₂ ¹ ₁ ² ₂	.635	.014	.622	NiMo	Nephelite-basalt	Rhöngebirge	W.T. 359	Effusive; vitreous (?)
181	IV. ₂ ¹ ₁ ² ₂	.665	.020	.659	NiMo	Nephelite-basalt	Löbauerberg	W.T. 359	Effusive; vitreous (?)
182	IV. ₂ ¹ ₁ ² ₂	.726	.064	.636	NiMi	Leucite-basalt	New South Wales	R.G.S.N.S.W., VII, 302	Effusive
183	IV. ₂ ¹ ₁ ² ₂	.640	.008	.640	NiMo	Jacupirangite	Magnet Cove	W.T. 361	Intrusive
184	IV. ₂ ¹ ₁ ² ₂	.672	.012	.653	NiMo	Nephelite-basalt	Texas	W.T. 361	Effusive; vitreous (?)
185	IV. ₂ ¹ ₁ ² ₂	.665	.011	.650	NiMo	Nephelite-basalt	Texas	W.T. 361	Effusive; vitreous (?)
186	IV. ₂ ¹ ₁ ² ₂	.648	.017	.640	NiMo	Mellilite-basalt	Hegau	W.T. 361	Intrusive
187	IV. ₂ ¹ ₁ ² ₂	.609	.017	.591	NiMo	Mellilite-basalt	Hegau	W.T. 361	Effusive
188	IV. ₂ ¹ ₁ ² ₂	.633	.021	.625	NiMo	Mellilite-basalt	Westphalia	W.T. 363	Effusive
189	IV. ₂ ¹ ₁ ² ₂	.658	.020	.636	NiMo	Nephelite-basalt	Löbauerberg	W.T. 363	Effusive; vitreous
190	IV. ₂ ¹ ₁ ² ₂	.660	.008	.659	NiMo	Nephelite-basalt	Silesia	W.R.T. 61	Effusive
191	IV. ₂ ¹ ₁ ² ₂	.633	.007	.628	NiMo	Mellilite-basalt	Texas	W.T. 363	Effusive
192	IV. ₂ ¹ ₁ ² ₂	.653	.016	.629	NiMo	Nephelite-basalt	Hesse-Cassel	W.T. 363	Effusive
193	IV. ₂ ¹ ₁ ² ₃	.583	.058	.500	NiMo	Biotite-peridotite	Harz Mts.	W.T. 365	Intrusive
194	IV. ₂ ¹ ₁ ² ₂	.597	.016	.578	NiMo	Mellilite-basalt	Hegau	W.T. 365	Effusive
195	IV. ₂ ¹ ₁ ² ₂	.593	.019	.568	NiMo	Mellilite-basalt	Hegau	W.T. 365	Effusive

ABBREVIATIONS

A.J.S.=	<i>American Journal of Science</i> (New Haven)
A.R.G.C.C.G.H.=	<i>Annual Report of the Geological Commission of the Cape of Good Hope.</i>
Bull. 237=	Pirsson, "Igneous Rocks of the Highwood Mountains, Montana," <i>Bulletin No. 237</i> , U. S. Geological Survey (1905).
C.R.=	<i>Comptes Rendus de l'Academie des Sciences</i> (Paris).
J.G.=	<i>Journal of Geology</i> (Chicago).
R.C.R.=	Washington, <i>The Roman Comagmatic Region</i> , Carnegie Publication No. 57 (1906).
R.F.=	<i>Rosenbusch Festschrift</i> (Stuttgart, 1906).
R.G.S.N.S.W.=	<i>Records of the Geological Survey of New South Wales.</i>
W.R.T.=	Roth's <i>Tabellen</i> , arranged by Washington. <i>Professional Paper No. 28</i> , U. S. Geological Survey (1904).
W.T.=	Washington's <i>Tables</i> , 1884-1900. <i>Professional Paper No. 14</i> , U. S. Geological Survey (1903).
Nl=	leucite present in the norm.
No=	leucite not present in the norm.
Ml=	leucite present in the mode.
Mo=	leucite not present in the mode.